A Chemistry-Independent Microbattery with Enhanced Functionality

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ABSTRACT

This paper describes a novel form of a microbattery having characteristics not present in commercially available energy storage systems. The microbattery is based on porous materials with nanostructured surfaces. In a proposed reserve configuration, the solid electrodes of the microbattery are separated from the liquid electrolyte by a porous membrane that is modified on the nanometer scale to be either *superhydrophobic* or *superlyophobic*. When the microbattery is activated to provide power, a phenomenon called *electrowetting* causes the electrolyte to flow through the pores of the membrane, thereby contacting the electrodes to initiate the electrochemical reaction. Such architecture provides for an extremely long shelf life and chemistry independent functionality.

Keywords: microbattery, nanostructured surface, superhydrophobic,, superlyophobic, electrowetting, membrane, shelf life.

1 INTRODUCTION

Today, two top priorities concerning the use of batteries in portable electronics are: (1) Obtaining the most energy per unit weight and volume for the lowest cost, and (2) Converting energy from one form to another in a way that is fast, safe, clean and "*green.*" The problems are so relevant that companies, universities and governments throughout the world are searching for technically feasible and commercially viable solutions to meet the needs of the consumer, industrial, medical and military market sectors.

Arguably the most relevant battery type in use today for portable electronics is based on lithium chemistry because of its high energy density and both primary (disposable) or secondary (rechargeable) forms. Lithium batteries constitute $6 billion in sales globally and this number is increasing at compounded average annual growth rate of approximately 5%. However, there remain significant performance, safety and environmental issues and existing lithium batteries do not meet all of the needed power, size, cost, and manufacturability requirements demanded by certain modern portable electronics and microelectronics. In other words, form, fit and function is still in issue in many cases.

The general problems with batteries today that limit their use in certain portable electronic and microelectronic applications are:

- **All conventional batteries available today have limited or finite shelf life.** Due to constant current leakage that begins immediately after a battery is manufactured, they will eventually die *even if they are not used.*
- **The user cannot change or direct the way a battery works during operation.** Battery performance may be monitored, but not altered.
- **Battery size and form factor have not kept pace with the miniaturization of electrical components, microprocessors and integrated circuits.** As a result, maximum efficiency is not always achieved.
- **Some batteries contain chemicals that are not considered safe or environmentally friendly ("green").** This makes disposal a potential issue.

These problems represent an opportunity to improve on battery chemistry and structure. AlwaysReady, a subsidiary of mPhase Technologies, Inc., has met this challenge.

1.1 Battery Miniaturization

Small or thin batteries with high energy density and current capacity are in big demand. However, thin film batteries available today are still subjected to various levels of leakage currents. Micro-batteries are engineered differently and are a better alternative in applications where current leakage is a problem. The major applications that will create most of the market for thin film and micro-battery products are: smart cards, active RFID tags, wireless sensor systems, implantable medical devices, flexible displays and electronic paper. The markets for these batteries are expected to grow very rapidly and reach into the hundreds of millions to billions of dollars range over the next five years.

1.2 Need for Backup Power

In addition to primary and secondary batteries, there is another type referred to as a **reserve battery.** As the name implies, a reserve battery is used to supply backup power and is kept in an inactive state until it is called into action. The key differentiator of a reserve battery is that it really must always be ready to supply power *on* demand <u>or</u> *on command*, whenever and wherever necessary. There is little room for error and failure is not acceptable.

Reserve batteries are currently used in a few niche applications, mainly by the military in missiles, artillery shells, torpedoes, and other guided munitions. They are now being sought for smaller munitions such as mortars and micro-sized versions for small caliber "smart" bullets. .

However, current reserve batteries are comparatively large, complicated and expensive to produce. For example, one type contains moving parts such as springs or pistons that can malfunction. A thermal reserve battery takes a while to ramp up to power. These shortcomings pose technical challenges and potential commercial opportunities if the technology can be improved for military applications first and then adapted to other consumer, industrial, medical uses.

2 The AlwaysReady Reserve Microbattery

Our unique platform technology and novel energy storage and power management solution can conceivably be used as a primary or secondary battery, but our first prototype is reserve battery based on zinc and manganese dioxide to demonstrate the basic concepts. Although relatively easy to construct, it has limited commercial potential due to its relatively low capacity per unit volume of active material when scaled to a small size. Our main focus is on developing a lithium based reserve microbattery because of the technical benefits and commercial significance.

Our first prototype product is called the **AlwaysReady Reserve Microbattery.** It has typical dimensions of a few square centimeters at the base and is a few millimeters high as shown in Figure 1.

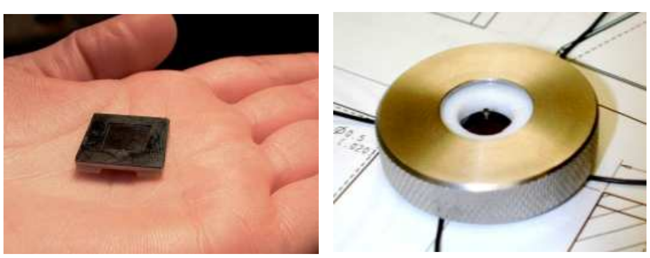

Figure 1. Example of the AlwaysReady Reserve Microbattery.as-made (left) and packaged (right).

The AlwaysReady Reserve Microbattery is designed to serve as a backup power supply that either complements or competes with small primary batteries and thin-film batteries in addressing the needs for emerging applications involving low power portable and microelectronic devices.

Our battery offers the following features and benefits:

- **Shelf-life longer than ten years** – no self-discharge (leakage current) until activated.
- **Activated on command** – triggered manually or automatically via Power On Command™[1].
- **Fast ramp up to power -** supplies electrical current in less than one second.
- **Programmable logic** – extends battery lifetime and electronics run time.
- **Versatile chemistries** – expands battery functionality and operating range through customization.
- **Flexible packaging** – variable form factor allows different sizes and shapes.
- **Low cost manufacturing** – compatible with state-of-the art silicon semiconductor fabrication and processing techniques.
- **Environmentally safe disposal** – uses "green" materials where possible and offers patented chemical neutralization process if needed.

2.1 Principle of Operation

Our technology exploits the phenomenon of *electrowetting* - the ability to electrically manipulate the way liquids behave when in contact with a solid or porous surface [1]-[3]. Water will bead up on a surface that is *superhydrophobic*[2], but can be made to move or spread out by electrowetting. The same is true for an organic liquid if the surface is *superlyophobic* [4].

We have been exploiting the same phenomena in our Reserve Microbattery by manipulating the liquid electrolyte via a silicon structure - a porous membrane - coupled with a unique battery architecture described below.

[1] **Power On Command™** is a key differentiating feature of the AlwaysReady Reserve MicroBattery by which it may be locally or remotely activated by the user.

[2] A **superhydrophobic** solid material has a surface that is extremely difficult to wet with water. Rather than spread out uniformly, the water will bead up into droplets with so-called large contact angles measured relative to the solid's surface. The property is a function of surface roughness and surface chemistry. On the other hand, a **superlyophobic** material has a surface that is extremely difficult to wet with organic or non-aqueous liquids such as alcohol or oil.

The AlwaysReady Reserve Microbattery has proven adaptable to a wide range of chemistries, with the initial development based on zinc manganese dioxide (Zn/MnO_2), and the current development focused on the higher-energy density lithium manganese dioxide (Li/MnO_2). A potential future rechargeable battery is a lithium-based chemistry that can be implemented with the same proven architecture.

As shown in the Figure 2, in the **Reserved or Initial State** there is zero output voltage. The triggerable membrane is the “barrier” that keeps the electrolyte separated from the positive and negative electrodes. In the **Activated State**, a triggered voltage pulse has been applied between the membrane and the electrolyte to allow the electrolyte to flow into the electrode chamber to start the chemical reaction and hence producing the output voltage (1.5 V for Zn/MnO_2 and 3V for Li/MnO_2).

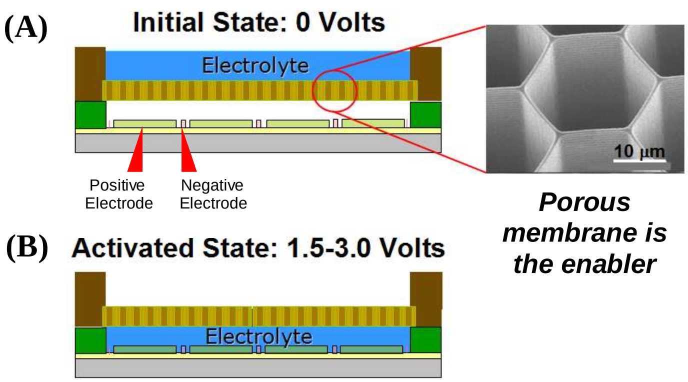

Figure 2. Basic operating principle of AlwaysReady Reserve Microbattery. In the initial state (A), the liquid electrolyte sits on top of the porous membrane and does not come into contact with the electrodes. As a result, no power is generated or wasted. In the activated state (B), the electrolyte flows through the membrane and makes contact with the electrodes so that an electrochemical reaction occurs and power is generated.

2.2 Power Management

A key differentiating feature of the AlwaysReady Reserve Microbattery is Power On Command™. This feature is the ability of the user to locally or remotely activate the battery, in effect turning it “on” from an inactive or reserve state. Prior to activation, the battery's chemicals remain separate, therefore supplying no power. Activation is initiated on the user’s command causing the chemicals to mix, electrochemical reactions to occur, and power to be supplied to an electronic device.

Our battery’s arrayed cell configuration extends control via Power on Command from a single cell to multiple cells. The array concept is a method of segmenting the battery into groups of individual cells that can be independently addressed and activated at different times, as needed. Because they are independent in form and function, each cell in the array can be of a different energy density or even a different chemistry (electrodes and electrolytes). This potentially allows for a battery array to be built in which individual cells address the unique power requirements of different subsystems, or can adapt to deliver power continuously under varying temperature extremes from very hot to very cold. In these cases, portions of the battery array are addressed and consumed sequentially as needed, thus preserving remaining power for later use and extending the useful life of the electronic device it is powering.

As an example, to demonstrate extremely long active life, an AlwaysReady Reserve Microbattery that is designed to provide power continuously for ten years can be clustered into an array of identical cells that are designed to turn-on sequentially as one group dissipates and eventually dies. Just before one group of cells dies it triggers on a neighboring group. Therefore, three cells could provide up to 30 years (3 x 10 years each) of uninterrupted service. The effect is shown in Figure 3 for a three-cell array.

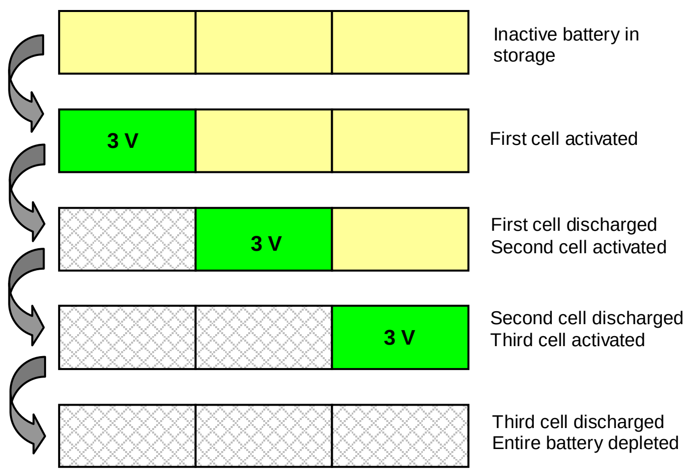

Figure 3. Illustration of an AlwaysReady Reserve Microbattery consisting of a three-cell array. The battery begins producing power when the first 3 V cell in the battery is activated. When that cell dies, the second cell is triggered. When it dies, the third cell is turned on. The battery is fully discharged when all three cells are depleted.

The selective activation of cells can be programmed electronically. For continuous operation in a changing environment from very hot to very cold, different electrode and electrolyte chemistries can be employed that can be triggered on as needed to match environmental conditions. This programmable feature can be used effectively to power remotely deployed sensors for military and other specialty applications, as well as implantable medical devices.

3 Technical Challenges and Risk Mitigation

AlwaysReady is currently designing and developing Reserve Microbattery prototypes with the understanding that successful commercialization will require risk mitigation in three areas:

- Battery design and packaging
- Manufacturing costs
- Safety and environmental issues

For complicated applications in which battery activation by electrowetting is used or addressable arrays of cells are triggered for improved power management, additional miniature external circuitry will be required, which will impact the cost of these battery configurations. This is typical for advanced "smart" batteries, as electronic logic circuitry is used, for example, in all multi-cell rechargeable lithium battery configurations to provide voltage smoothing and monitoring.

We are currently working on lab- and pilot-scale equipment to fabricate battery prototypes. However, we believe that well established plant-scale manufacturing processes already exist that can be accessed on a contract basis or purchased. When large scale, high volume production is in place, we expect to achieve cost advantages comparable to those that other traditional battery manufacturers have realized.

We have chosen lithium chemistry for our Reserve Microbattery because of its excellent energy characteristics and wide commercial acceptance. The procedures for working with lithium are well documented in the technical literature and battery manufacturers that we would work with are experienced in its safe and efficient handling. The lithium chemistry used in our Reserve Microbattery is considered relatively benign from a safety standpoint compared to other available chemistries. Furthermore, the amount of active material used in each of our micro-cells is quite small in weight and volume, reducing risk during preparation, in use and at the end of life. Nonetheless, depending on the application, it could be neutralized to ensure safe disposal.

In conclusion, we have demonstrated a working reserve microbattery prototype based on superhydrophobic and superlyophobic nanostructured surfaces. It has three distinct features: first, an inactive state in which electrolyte is completely separated from the electrodes by the nanostructure; second, battery actuation by a voltage pulse, and third, stable voltage generation. We continue to refine and characterize battery parameters to compare them with the conventional battery structures. We are addressing battery packaging and manufacturing issues. The architecture proposed is a disruptive technology, a technology that provides a fundamental paradigm shift in battery and power technology.

ACKNOWLEDGEMENTS

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